A techno-economic evaluation of a small-scale fluidized bed gasifier for solid recovered fuel

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ABSTRACT

This paper reports a technical assessment for an air gasification plant for energy recovery from 5000 t/y of a solid recovered fuel (SRF). This was obtained as one of the output streams from a sorting platform of municipal solid waste, which aims to minimize the utilization of the annexed landfill. The case study analysis was based on data provided by a pilot-scale bubbling fluidized bed gasifier, having a feedstock capacity of about 70 kg/h of the obtained SRF. The tests indicate that the SRF can be converted into a syngas of valuable quality for energy applications. A plant configuration, which includes a bubbling fluidized bed reactor, a mild combustor, a 400 kWe Organic Rankine Cycle generator and an air pollution control system, was defined and described in detail. The standard accounting items related to investment and operating costs were estimated on the basis of official manufacturer's specifications and information: they indicate an economic sustainability only in presence of an incentive tariff for energy production. A material flow analysis indicates that the implementation of the small-scale gasifier could allow a landfill volume saving of more than 10,000 m³/y.

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1. Introduction and framework

Municipal solid waste (MSW) contains remarkable amounts of materials, mainly derived from packaging, which can efficiently be recycled for a sustainable recovery of resources [1,2]. Recycling processes very often ensure a remarkable saving of primary resources, a strong reduction of amounts of wastes to be disposed, and a huge limitation of emissions arising during primary productions [3]. On the other hand, recycling is not always a fully sustainable process: all the waste recycling processes need materials and energy and generate residues; not all the materials can be efficiently recycled, i.e., without excessive consumption of resources; and only few materials can be recycled for many times. This simply means that recycling, as any other single waste management practice, is not suitable for all waste streams [4]. A modern integrated management system will be really sustainable if it includes effective waste prevention programs, good source separation practices, all the possible recycling activities not entailing excessive consumption of resources, efficient biological treatments of organic fractions as well as energy recovery processes from materials that cannot be efficiently recycled [3,5,6]. In particular, the large stream of the dry organic fraction of MSW that cannot conveniently be recycled or biologically treated, together with the high heating value residues from specific recycling chains, as those of paper and plastics, can be both processed into solid recovered fuel [7,8]. SRF is a sufficiently homogeneous fuel intended for use in an energy recovery facility, having composition and characteristics defined by a European standardization [9].

A sustainable process for thermochemical exploitation of SRFs is gasification in fluidized bed reactors. Gasification converts solid fuels to a synthesis-gas through a series of heterogeneous and homogeneous phase, gas-forming reactions, occurring in presence of an amount of oxidant strongly lower than that required for the stoichiometric combustion [10,11]. The resulting syngas is a fuel gas that contains large amounts of not completely oxidized products (mainly CO, H_2 and lower contents of CH_4), together with different organic (tar) and inorganic (H_2S, HCl, NH_3, HCN and alkali metals) impurities and particulates. Fluidization is a very promising gasification technology due to the high-quality gas–solid contact and the very efficient mass and heat transfers. Its intrinsic process flexibility is able to accommodate variations in fuel quality, to allow the utilization of different fluidizing agents, reactor temperatures and gas residence times, to add reagents along the reactor height and finally to operate with or without a specific catalyst [12]. Today, there is a great interest for SRF gasification for energy production, mainly from small- and medium-scale plants [13–15], even though a very large-scale fluidized bed plant has been recently put in operation in Finland [16].

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The paper describes the results of a research program aimed at assessing the technical and economic feasibility of a fluidized bed gasifier able to treat a mass flow rate of about 5000 t/y of SRF. The fuel is obtained as one of the output solid streams from a sorting platform of MSW collected in an urban area of Molise, in the middle of Italy. The unit produces the following: (i) different streams of plastics, ferrous and non-ferrous metals, which are sent to the market; (ii) a wet biodegradable fraction, which is composted and utilized in-situ as capping material for the annexed landfill; and (iii) a large stream of out-of-target materials, characterized by high calorific value, which is classified as an SRF and can be fed into a fluidized bed gasification plant for energy generation. This combination of processes and technologies, where the proposed SRF gasifier can be included, is schematically represented in Fig. 1: the final aim is to limit the mass flow of waste sent to the ultimate disposal and then optimize the utilization of landfill space. A number of tests were carried out by feeding the SRF in a pilot-scale bubbling fluidized bed gasifier (BFBG) in order to obtain data for a reliable technical evaluation. The experimental results were processed to obtain data and information useful to define appropriate design solutions and a suitable plant configuration for a technical and environmental practicable energy generation. Finally, an evaluation of main economic parameters was developed on the basis of official specifications and information of plant manufacturers.

2. The pilot-scale reactor and the tested SRF

The pilot-scale bubbling fluidized bed gasifier has a feedstock capacity of 70 kg/h of the selected SRF and a maximum thermal output of about 400 kW. Its main design and operating parameters are summarized in Table 1. It is noteworthy that the size of the reactor, which has an internal diameter of 0.381 m, is sufficiently large to avoid remarkable scale-up effects. Thereby, the results of experimental activity can be utilized to estimate the composition and the specific yield of the produced syngas in larger commercial facilities, as already made in previous studies [17,18]. The configuration of the experimental facility can be deduced by the quantified flow sheet of Fig. 2, which reports the mass flow rate (in kg/h) of the gaseous and solid streams under a specific

Table 1
Main design and operating parameters of the pilot-scale BFB gasifier.

Geometrical parameters	Internal diameter: 0.381 m, total height: 5.90 m, reactive zone height: 4.64 m, wall thickness: 12.7 mm
Feedstock capacity	Up to 70 kg/h (with the selected SRF)
Thermal output	Up to about 400 kW
Typical bed amount	145 kg
Oxidizing agent	Air
Feeding system	Over-bed water-cooled screw feeder
Range of bed temperatures	700–950 °C
Produced gas treatments	Cyclone, scrubber, flare
Safety equipments	Water seal, safety valves, rupture disks, alarms, nitrogen line for safety inerting

operating condition. In particular, the stream of the bottom ash extracted from the gasifier is not reported since a test run was never longer than few hours and the accumulation of ash inside the bed is consequently limited (its flow rate for the specific test is 6.55 kg/h as reported in the diagram). For longer test runs, the bottom ash is extracted periodically by means of a pipe located in the middle of fluidizing gas distributor and equipped with a bayonet valve. A more detailed description of the pilot-scale gasification plant and its experimental procedures can be found in [15]. Here it is important to highlight that, under the selected operating values of equivalence ratio ER (defined as the ratio between the oxygen content of air supply and that required for the stoichiometric complete combustion of the fuel effectively fed to the reactor) and air preheating temperature, the reactor was always operated under conditions of thermal and chemical steady state, and without any thermal assistance of external heaters [15]. In other words, all the tests were carried out under autothermal conditions, i.e., the same under which the reactor will be operated in the real plant. It is also noteworthy that, taking into account the relevance of these measurements for the technical and economic feasibility of the process, two methods were used to evaluate the amount and composition of tar. The first, conservative method was utilized for quantitative determination of tar concentration in the obtained producer gas: it assumes that tar is composed
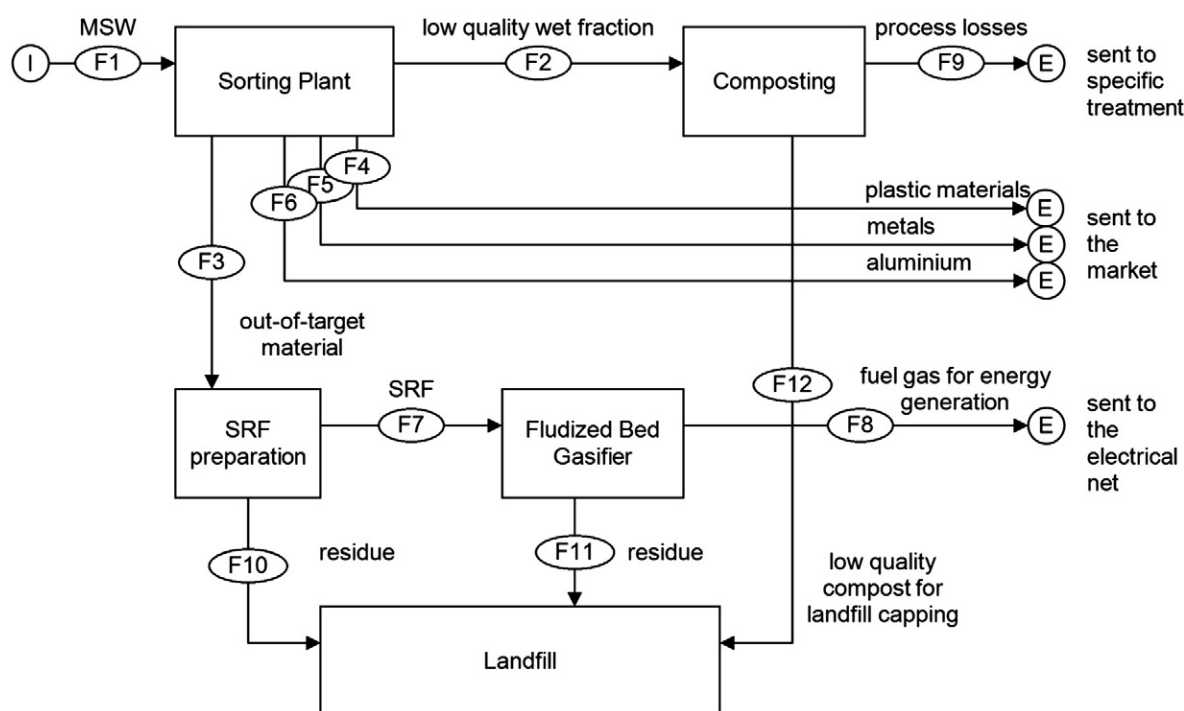

Fig. 1. Schematic of the proposed waste management system where the energy generation in a fluidized bed gasifier of SRF can be included. I = input stream; E = output stream; i = 1–12 indicates the different solid streams.
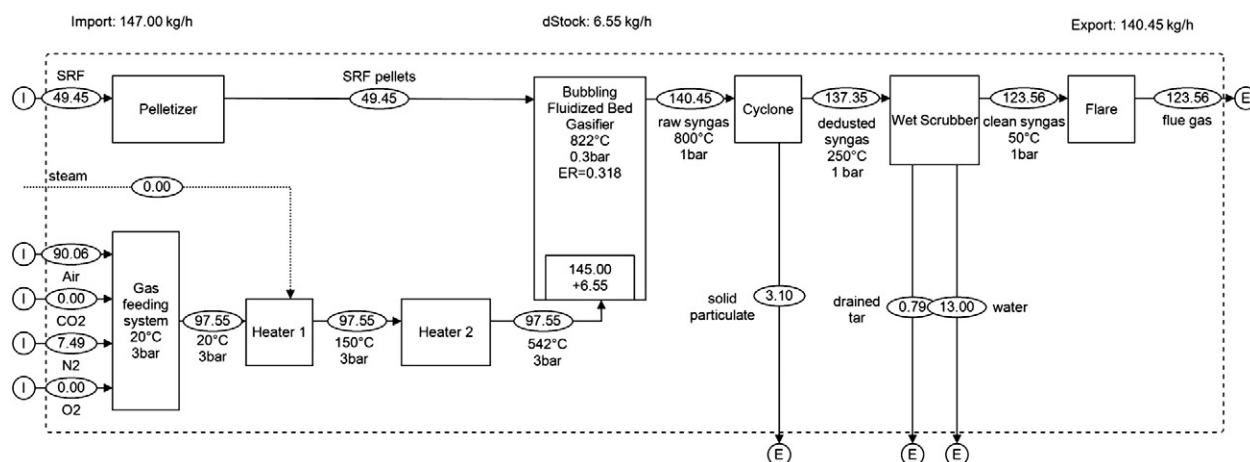
Fig. 2. The quantified flow sheet of the pilot-scale gasification plant, when it was operated with the selected SRF at a value of ER = 0.318. The mass flow rates of gas and solid streams are expressed in kg/h. The values of gauge pressure are expressed in bar. I = input stream; E = output stream; Import = total mass flow rate in input to the system; Export = total mass flow rate in output from the system; dStock = total mass flow rate stocked in the system.

of all organic compounds with a molecular weight larger than benzene, excluding soot and char, and conservatively imputes to the tar amount the whole carbon loading which, as a result of a mass balance on atomic species, cannot be attributed either to the producer gas or to the solids collected at the cyclone or present inside the bed. The second procedure was instead used to detect tar compounds belonging to the classes between 2 and 5 of the classification proposed by the ECN-Energy research Center of the Netherlands [19]: it samples the condensable species by means of a system composed of four in-series cooling coils, a suction pump and a flowmeter and then sends them to offline analyses, with a specific pre-treatment in a Perkin-Elmer Clarus 500 gas chromatograph coupled with a mass spectrometer [15].

The utilized SRF, produced by the above-mentioned commercial sorting platform located in the middle of Italy, was mechanically processed to obtain mono-size cylindrical pellets, 5 mm of diameter and 30 mm of length, in order to avoid any effect related to fuel size and to increase the density of material to be fed into the gasifier. Table 2 reports the ultimate analysis and low heating value of the pelletized SRF: the ranges of variation are rather limited, taking into account that the originally unsorted residual waste was collected in different period of the year and from different catchment areas.

Table 2
Main chemical properties of the tested SRF.

Ultimate analysis, %$_{wt, ar}$	
C	41.2–45.4
H	6.0–6.5
N	0.66–0.70
S	0.1–0.3
Cl	0.1–0.2
O (by diff.)	22.9–24.2
Moisture	3.7–9.1
Ash	18.5–20.4
Low heating value, kJ/kg$_{SRF, ar}$	
Theoretical[a]	16,600–21,300
Experimental[b]	16,500
Ash melting temperature	
Half fluid temperature (HFT),[c] °C	1,420–1,730

ar = as received; db = on dry basis.
[a] The range is 16,600–18,900 by using the relationship of Dulong and Petit [20]; the range is 18,600–21,300 by using the relationship of Channiwala and Parikh [21].
[b] The measurement was made on the stock of SRF used for the specific tests reported in table 3.
[c] [22].

3. The configuration of the waste-to-energy system

The configuration of the gasification-based waste-to-energy system was defined on the basis of the following design specifications. The plant must be fed with about 5000 t/y of the described SRF. Due to the size of the plant and on the basis of previous and similar techno-economical analyses [17,18], the atmospheric BFB air gasification was defined as the conversion technology to be adopted. The plant can be seen as a combination of the three sections of syngas production, cleaning and utilization. The relative succession of the utilization and cleaning sections defines two possible configurations: the "heat gasifier," where the syngas is directly burned and the obtained flue gases are then cleaned in an air pollution control (APC) unit, and the "power gasifier," where the syngas is first efficiently cleaned and then burned in a high efficiency energy generation device. The following paragraphs investigate the characteristics of each of these sections for a plant able to treat 5000 t/y of the tested SRF.

3.1. The gasification section

As mentioned above, data obtained by the experimental activity on the pilot-scale reactor have been utilized for the design of this section. The BFBG was operated by injecting the SRF into a bed of olivine particles fluidized at a fixed superficial gas velocity of about 0.7 m/s and temperatures of about 850 °C, under different values of equivalence ratio, in order to quantitatively assess its behavior in the fluidized bed gasification process. Table 3 lists the experimental results of two air gasification tests that were assumed as design data. They were obtained under conditions of thermal and chemical steady state and are part of a series of tests reported and discussed in detail elsewhere [15]. In particular, the carbon conversion efficiency (CCE) is defined as the fraction of carbon flow rate entering the reactor with the SRF that is converted to gaseous products (CO, CO_2, CH_4 and C_nH_m), while the cold gas efficiency (CGE) is defined as the fraction of the chemical energy of the SRF that is transferred to the producer gas. The experimental activity indicates that the obtainable syngas cannot easily meet the severe requirements of gas engines or turbines, mainly for the high contents of dust and tars. The tar composition is reported in Table 3, together with the condensation temperature and the class of the recalled ECN classification of each specific compound. The large content of tars belonging to class IV (i.e., compounds having 2 or 3 rings, which condense at low temperatures even at very low concentrations) and class V (i.e., those having more than 3 rings, which condense at high temperatures at low concentrations), and above all that of unidentified compounds, suggests to adopt a configuration where the hot syngas is directly sent to an adequate gas

Table 3
Operating conditions and experimental results of all the tests.

Operating conditions		
ER	0.302	0.318
Air/Fuel (A/F), kg_{air}/kg_{SRF}	1.73	1.82
Bed amount, kg	146	146
SRF flow rate, kg_{SRF}/h	51.9	49.4
Fluidizing velocity, m/s	0.72	0.73
Air preheating temperature, °C	329	542
Process results and parameters		
Overall fluidizing velocity, m/s[a]	0.79	0.82
Bed temperature at steady state, °C	879	898
Syngas temperature at reactor exit, °C	801	822
Syngas production (on dry basis), m^3_N/kg_{SRF}	1.91	2.04
Syngas production (on dry basis), kg_{syngas}/kg_{SRF}	2.34	2.56
Syngas LHV, kJ/m^3_N	5160	4910
Specific energy, kWh/kg_{SRF}	2.78	2.79
Carbon conversion efficiency	0.81	0.92
Cold gas efficiency	0.61	0.61
Syngas composition		
N_2, %	61.86	60.66
CO_2, %	12.83	14.04
CO, %	10.40	12.73
H_2, %	8.24	7.08
CH_4, %	4.35	3.33
C_2H_4, %	2.05	1.78
C_2H_6, %	0.04	0.07
C_2H_2, %	0.16	0.18
C_3H_6, %	0.02	0.02
C_6H_6, %	0.10	0.08
Elutriated fines, g/kg_{SRF}	102.8	62.7
Elutriated carbon fines, g/kg_{SRF}	20.2	24.2
Tar, g/m^3_N[b]	39	5
HCl, mg/m^3_N[c]	117.5	2.1
H_2S, mg/m^3_N[c]	39.1	0.5
NH_3, mg/m^3_N[c]	39.6	2.7
Tar composition[d]		
Naphthalene, $C_{10}H_8$ (T_b = 218 °C, class IV), %	6.0	8.4
1-Metilnaphtalene, $C_{11}H_{10}$ (T_b = 241 °C, class IV), %	7.0	-
2-Metilnaphtalene, $C_{11}H_{10}$ (T_b = 241 °C, class IV), %	3.5	-
Acenaphthylene, $C_{12}H_8$ (T_b = 280 °C, class IV), %	4.0	-
Phenantrene, $C_{14}H_{10}$ (T_b = 336 °C, class IV), %	-	0.7
Anthracene, $C_{14}H_{10}$ (T_b = 340 °C, class IV), %	-	1.2
Fluoranthene, $C_{16}H_{10}$ (T_b = 384 °C, class V), %	-	0.3
Pyrene, $C_{16}H_{10}$ (T_b = 404 °C, class V), %	29.5	0.4
unidentified, %	50.0	89.0

[a] This value takes into account the produced syngas, by assuming that it was completely generated inside the bed.
[b] This value was conservatively determined on the basis of mass balance on atomic species.
[c] These values refer to the reactor exit, then before the cleaning gas system.
[d] T_b is the condensation temperature; the number of the class refers to the ECN classification [19].

Table 4
Main parameters of the proposed BFB air gasifier.

Annual SRF throughput	5230 t/y
Plant availability	300 d/y
Nominal net electric power output	400 kWe
Nominal fluidizing velocity	0.72 m/s
Internal diameter of BFB gasifier	1.5 m
Height of freeboard section	4.3 m

3.2. The syngas combustion section

The proposed syngas combustion section utilizes an innovative technology, known as mild combustion. The driving idea is optimizing fuel gas conversion in terms of energy consumption and pollutant emission, and at the same time saving the configuration of traditional processes. Stability, near-homogeneous temperature and concentration profiles, reduction and abatement of pollutants as well as very specific oxidative structures, different from the traditional thin flame, allow to consider mild combustion as a very interesting process in terms of environmental sustainability [26]. The practical difference between conventional flame and mild firing modes is remarkable, as shown in Fig. 3. The fuel gas and the oxidizer are separately injected in order to enhance the local recirculation of inert flue gases and to obtain a strong dilution of both the streams before the reaction. In the combustion of the syngas from SRF gasification, this dilution effect is further enhanced by the high content of nitrogen and carbon dioxide in the fuel gas. The very high syngas temperature expected at the BFBG exit (more than 800 °C, as reported in Table 3) is a further advantage. In the mild combustion mode, the pollutant formation and the heat flow distribution as well as the ranges of temperatures and concentration are quite different from the conventional, burner-stabilized flame (Fig. 4), and this may be exploited for practical purposes. The effect of the low melting temperature of the inorganic residues contained in the syngas and the resulting effect on slagging and plugging of the boiler convective pass become easier to be controlled, as well as corrosion and material durability, improving the overall reliability of the system. The lowering of peak temperature strongly reduces NOx formation, while the good uniformity in temperature and oxidation reactions limits the production of dioxins and furans (PCDD/F) as well as that of PICs (products of incomplete combustion) and PAHs (polyclyclic aromatic hydrocarbons), even when a low air excess is used [27,28].

3.3. The energy generation section

An Organic Rankine Cycle (ORC) has been selected for this section due to its higher performances compared with those of a steam cycle, when there is a low and greatly variable thermal power input. ORC is based on the vaporization of a high pressure liquid which is in turn expanded to a lower pressure (thus releasing mechanical work); the low-pressure vapor is then condensed and pumped back to the high pressure. Thereby, the ORC involves the same components as a conventional Steam Rankine Cycle but the organic compound utilized as working fluid has a lower boiling temperature and allows power generation from low heat source temperatures. This implies a simpler layout: there is no water–steam drum connected to the boiler, and one single heat exchanger can be used to perform the three evaporation phases (preheating, vaporization and superheating) [29]. The ORC works well at low temperatures, typically between 100 °C and 400 °C, because evaporation takes place at lower pressure and temperature, expansion ends in the vapor region (hence superheating is not required), and the smaller temperature difference between evaporation and condensation leads to a much smaller pressure drop ratio which allows the use of single stage turbines [30].

ORC has a series of advantages (mainly, the high efficiency of turbine also in cogeneration mode and the absence of blade erosion due to the

burner [10]. This "heat gasifier" configuration implies lower efficiencies in electric energy conversion but allows a high technical reliability of the plant and a potentially complete exploitation of the tar heating content. It offers some remarkable advantages over the direct combustion of solid fuels [8,10]: the combustion of low molecular fuel gases is more efficient and cleaner, due to the improved mixing of reactants; the homogeneous-phase combustion allows an easier control and a more continuous operation; a lower excess of air is used, which in turn implies lower thermal losses at the stack; there is an intermediate step between gasification and combustion where gas clean-up can potentially occur; the system appears more conveniently applied on a relatively small scale. The data reported in Table 3 were eventually processed by means of the relationships of fluidization engineering [23–25] in order to define the main geometrical parameters of the bubbling fluidized bed gasifier, which are synthetically listed in Table 4.
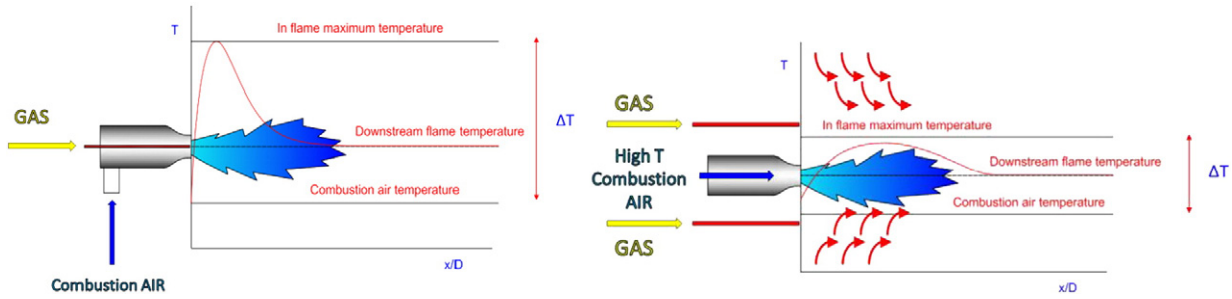
Fig. 3. Patterns and temperature distributions of conventional (left) and mild (right) flames (redrawn from [27]).

avoided formation of droplets during superheated vapor expansion) that can result in operating benefits such as simple startup and shut-down operations, no need of licensed personnel, excellent performance for partial load (minimum load of about 10% of base load, rapid response to transient), high reliability (>98%) and low noise emission [29]. The standard systems use poly-siloxanes working fluid and are available in a power range from 0.1 to 3 MW$_e$. The heat is transferred from the thermal source to the ORC cycle through the use of diathermic oil or saturated steam at low pressure; electrical efficiency of these modules is affected by hot and cold source temperatures and may vary in the range 8–20% [30]. The process design for the SRF gasification plant refers to a 400 kWe ORC unit commercialized by Turboden [31], whose technical data are listed in Table 5. In particular, the selected unit is equipped with an air heater able to reduce the temperature at the stack discharge, so allowing reaching an overall boiler efficiency of 87%.

3.4. The air pollution control section

The fluidized bed gasification process coupled with a syngas mild combustion allows a sufficiently reliable process control. As a specific cleaning device, it is necessary to minimize emissions of micropollutants, such as dioxins, particulate matter and heavy metals. The proposed configuration utilizes a baghouse able to guarantee particulate concentrations much lower than the standards imposed by normative and to provide at the same time high reliability and low operation costs. Moreover, the cake formed over the filter bags contributes to a good control of acid gases, heavy metals and dioxins since it is an ideal substrate to the action of sodium bicarbonate or hydrated lime for the neutralization of HCl, H$_2$S and SO$_x$ and that of pulverized activated carbon for the adsorption of Hg, Cd, low boiling heavy metals and dioxins [11]. The process is

totally dry so that no aqueous effluents have to be treated. The flow diagram of the whole process is reported in Fig. 5. The relative legend is provided in Table 6, where the main parameters of all the involved gas and solid streams are also reported.

3.5. The waste management system for the case study

The waste management system where the proposed SRF gasifier should be included is described in Fig. 6 as a quantified flow sheet, with the detail of the mass flow rates in input and output to or from each unit. The composition of municipal solid waste and the transfer co-efficients between the units are those of a material and substance flow analysis developed for a waste management planning proposal for the specific catchment area [6]. Data reported in Fig. 6 indicate that the management scheme could allow a substantial diversion from landfill, i.e., 1,963–1,069 = 894 t/y instead of 5,811 t/y. On the basis of assumption made in the mentioned proposal of waste management planning, this implies a saving of landfill volume of more than 85% (1,870 m^3/y instead of 12,100 m^3/y).

4. Economic evaluations

A reliable assessment of the economic feasibility of a small-scale waste-to-energy plant is generally not easy. Many specific and local factors as well as plant management, energy revenue, but also, plant lifetime and reliability, emission limits, disposal cost of solid residues, etc., can largely affect the fixed and the variable cost items [32]. Although additional feed-in tariffs or subsidies for energy generation from not conventional sources could be sometimes locally applied, the quantity of SRF being treated (annual throughput), the generated
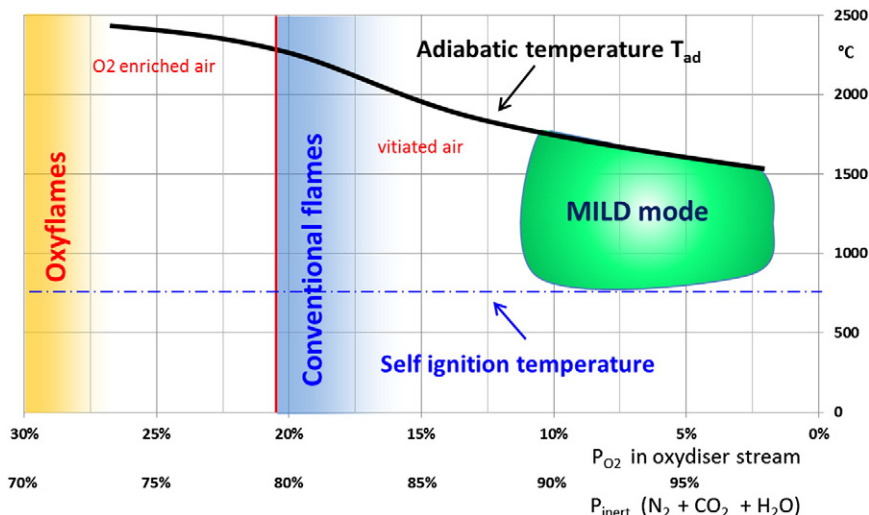

Fig. 4. Range of temperature and oxydizer concentration for flameless (mild) combustion with respect to conventional flames and oxyflames (redrawn from [27]).

Table 5
Technical specifications for the ORC turbine included in the proposed configuration, assuming an overall boiler efficiency of 87% [31].

Thermal energy input	2260 kW
Diathermic fluid	Thermooil
Inlet temperature (base load)	300 °C
Outlet temperature (base load)	250 °C
Organic fluid	Silikon oil
Thermal output (condenser)	1408 kWth
Cooling fluid	water
Inlet temperature (base load)	60 °C
Outlet temperature (base load)	80 °C
Net electric power output (base load)	400 kWe
Net electric efficiency (base load)	17.7%

energy (energy performance) and the emission limits (environmental performance) can remarkably change the cost of equipment. Taking in mind these difficulties, the different items that have to be considered for the economic assessment of the proposed plant are discussed in the next paragraphs. The adopted models for total plant costs and operating costs utilize average industrial standards based on official technical offers and information from manufacturers. The economic evaluations reported in the following have then an absolute value and can be used to be compared with the economic performances of similar or related technologies. It is important to highlight that the gasification plant of the examined case study should be preferentially evaluated as part of the specific integrated management system reported in Fig. 6.

Table 6
Legend of the process flow diagram for the SRF gasification plant reported in Fig. 6, together with the quantification of its flow streams.

Stream no.	Stream name	Temperature, °C	Pressure, bar	Mass flow rate, kg/h	Enthalpy flow, kJ/s[a]
1	SRF feed	25	1	726	−1376
2	Atmospheric air	25	1	1278	0
3	Atmospheric air	64	1.25	1278	14
4	Fluidizing air	500	1.25	1278	177
5	Hot raw syngas	900	1.15	2004	−1201
6	Hot raw syngas	715	1.15	2004	−1364
7	Dedusted syngas	715	1.15	1810	−1378
8	Collected fines	715	1.15	194	14
9	Atmospheric air	25	1	3800	0
10	Atmospheric air	33	1.05	3800	9
11	Combustion air	254	1.05	3800	248
12	Hot combustion flue gas	950	1	9626	−3732
13	Warm combustion flue gas	260	1	9626	−5998
14	Combustion flue gas	180	1	9626	−6237
15	Recirculated flue gas	180	1	4016	−2602
16	Flue gas to the filter bags	180	1	5610	−3635
17	Sodium bicarbonate	25	1	10	–
18	Activated carbon	25	1	0.5	–
19	Cleaned gas to the stack	180	0.9	5610	−3635
20	Diathermic oil	300	1	50000	−25671
21	Diathermic oil	250	1	50000	−28030

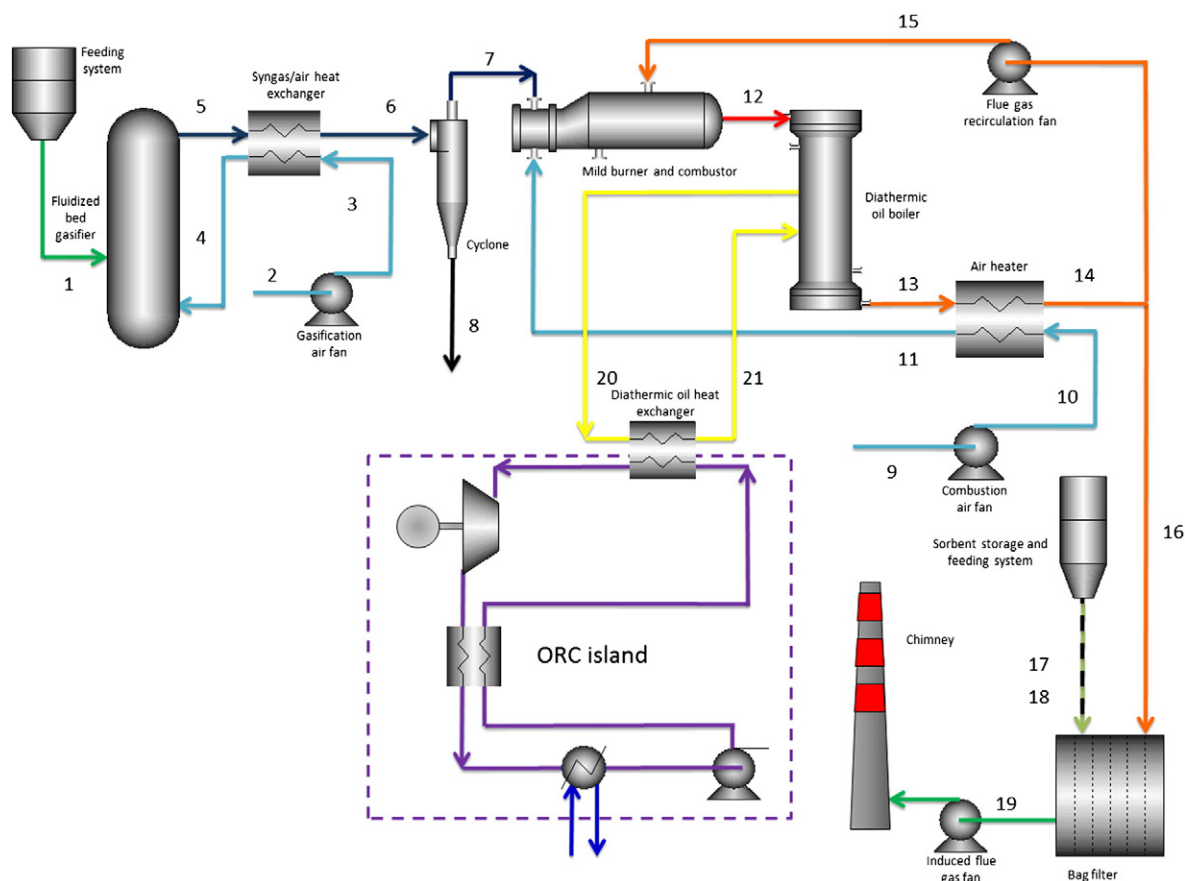[a]Based on standard enthalpy of formation

Fig. 5. Process flow diagram for the SRF gasification plant, with the indication of the name of each component (broken line limits the ORC cycle).
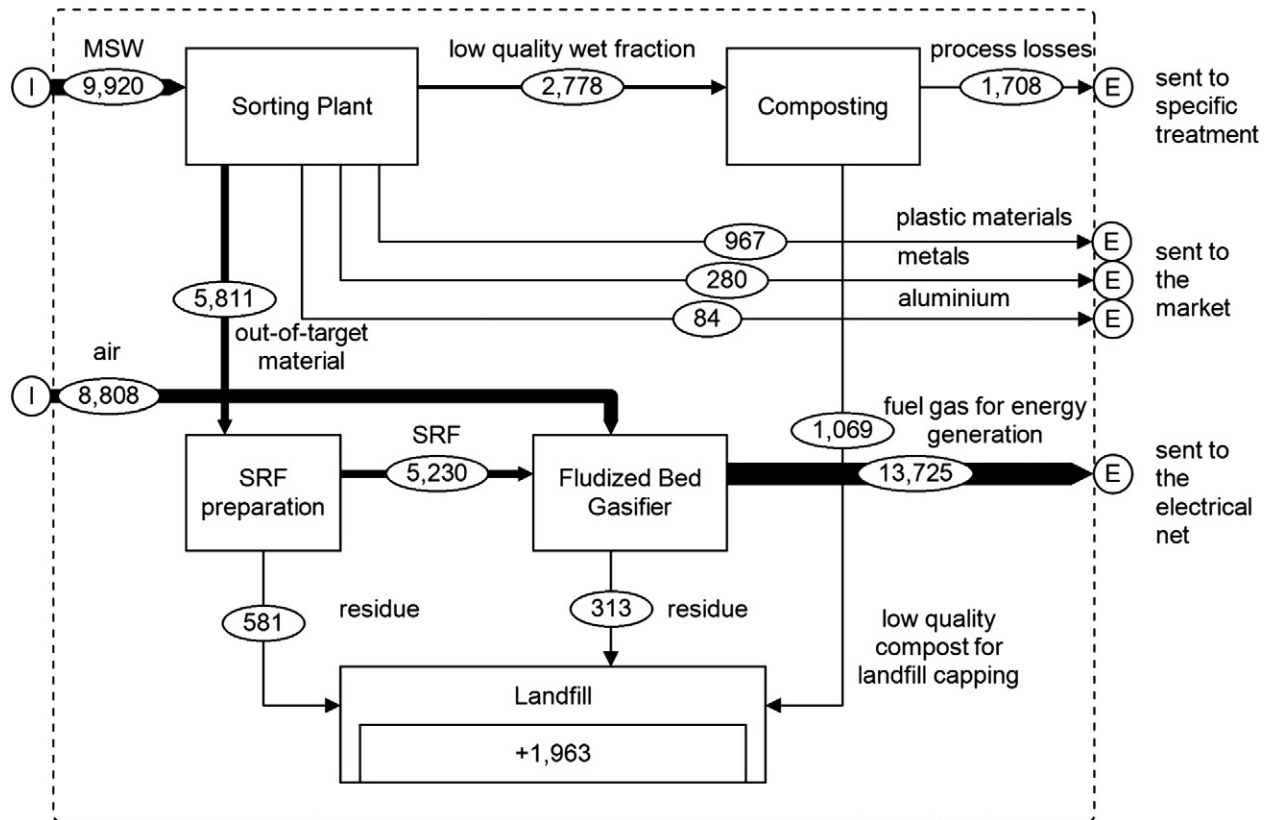
Fig. 6. The quantified flow sheet for the case study, i.e., for the waste management system where the proposed fluidized bed gasifier of SRF can be included. The transfer coefficients are based on [15]. I = input stream; E = output stream; Import = total mass flow rate in input to the system; Export = total mass flow rate in output from the system; dStock = total mass flow rate stocked in the system.

Table 7
The items of cost for the evaluation of the capital expenditure (CapEx) for the proposed 400 kWe plant.

Plant size	5230 t/y (400 kW$_e$)
Civil works and buildings	150 k€
Gasification system	660 k€
Feeding section	60 k€
Gasifier	500 k€
Auxiliaries (fans, pilot burner, etc.)	60 k€
Ash extraction system and storage	40 k€
Syngas/air heat exchanger	25 k€
Cyclone dust collector	15 k€
Syngas combustor and diathemic oil boiler	190 k€
Burner and combustor	100 k€
Auxiliaries	30 k€
Diathermic oil boiler	60 k€
ORC complete system	700 k€
Air heater	25 k€
Sorbent storage and feeding system	20 k€
Bag filter	40 k€
Chimney	25 k€
Piping and insulation	100 k€
Instrumentation	40 k€
Syngas and flue gas analysis equipment	100 k€
Transformer room and parallel board	25 k€
Power lines and connection to the network	20 k€
PLC and data management system	50 k€
Electro-instrumental and pneumatic installation	50 k€
Service fluid lines and auxiliaries	50 k€
Safety devices	20 k€
Plant and civil works engineering (10% of the total value)	231 k€
Total CapEx	2,536 k€
	485 €/(t/y)

4.1. Total investment costs

The values in Table 7 show the capital expenditure (CapEx) related to equipment costs and civil engineering costs. It must be clear that in a more complete evaluation, which is strictly related to the specific plant, additional items have to be considered, as well as owners engineer costs, working capital costs and contingency funds. Taking into account the small size of the plant, it was encouraging to find a low specific investment cost of 485 €/(yearly ton of throughput), which seems to make this technology sufficiently competitive.

Table 8
The items of costs for the evaluation of the total cost of operation (OpEx) for the proposed 400 kWe plant.

Design assumptions			
Plant availability	7200 h/y		
Electrical power	2,880 MWh$_e$/y		
Operational expenditure (OpEx)			
Administration and management	50 k€/y	10 €/t	
Insurance and security	13 k€/y	3 €/t	0.5% of CapEx
Personnel	150 k€/y	30 €/t	1 person/shift
			5 people/year
SRF pelletization pretreatment	15 k€/y	3 €/t	
Power consumption	20 k€/y	4 €/t	0.12€/kWh
By-products and residue disposal	50 k€/y	10 €/t	
Auxiliary fuel (as natural gas)	15 k€/y	3 €/t	
Chemicals and additives	20 k€/y	4 €/t	
Maintenance and other consumables	40 k€/y	8 €/t	
Total OpEx	373 k€/y	75 €/t	

4.2. Total operating costs

The specific power production is estimated to be equal to 0.55 MWh$_e$/t$_{SRF}$, which is quite low but still within the range of the reference plants on the market. The main items that have been considered in the business plant evaluation are listed in Table 8. In particular, one person per shift is necessary to operate the plant and then, taking into account 3 shifts per day and that for resting, the personnel cost has been evaluated with reference to 5 people per year. The cost of the SRF is assumed to be that of its pelletization process, taking into account that it originates from a by-product of the sorting platform, which is so far sent to landfill disposal. The resulting overall operation cost is equal to 373 k€/y, i.e., 75 €/t$_{SRF}$, which is rather high with respect to other technologies [8] but of remarkable interest if compared with the average cost of ultimate disposal (i.e., in landfill [33] or conventional large-scale incinerators [34]), which is at the moment the only option for the examined case study. Some cost items present in the OpEx assessment (such as the mentioned cost of personnel) cannot be proportionally reduced as a function of the plant size, and then the small capacity of the gasification plant largely affects the final result. On the other hand, on the basis of the specific characteristics of the selected components, it can be expected that the proposed technology could have a rather wide margin of improvement (as that, for instance, related to the process automation that has been not considered at this stage), with a consequent reduction of operating costs.

4.3. Revenues

The gasification unit which is the focus of this case study is integrated in the management system quantified in Fig. 6, with two main sources of revenues: the electric energy sold to the national grid and the "avoided" landfill volume. The first item can be evaluated for the Italian market on the basis of specific incentive tariff, 88.74 €/MWh$_e$, which has been recently introduced: this should provide an overall revenue of 256 k€/y for energy produced from SRF. The second item is strongly dependent on the landfill gate fee, which varies in a rather wide range, for instance, in Italy from about 80 €/t to about 120 €/t [33,34]. Taking into account the effective saving of landfill space (which shows to be equal to 4,917 t/y and not 5,811 t/y in Fig. 6, keeping in consideration the bottom ash disposal), a minimum acceptable internal rate of return (IRR) of 12% and a payback time of 5.7 years can be achieved for a revenue from landfill saving of 472 k€/y. This value corresponds to an avoided disposal cost of 96 €/t$_{SRF}$, if the value of taxation is fixed at 31.4%, according to the current national fiscal imposition in Italy. Moreover, if a specific requirement is present in the plant area, a possible further revenue could be achieved by thermal power production, which for instance in Italy receives an incentive tariff of 10 €/MWh$_{th}$. The proposed economic assessment was not completed with a sensitivity analysis on the main profitability indices, as it was made for similar studies [17,18], due to the already mentioned difficulties in the evaluation of some crucial parameters and the peculiarity of the examined case study.

5. Concluding remarks

The techno-economic performances of a gasification-based small-scale waste-to-energy plant, having a nominal throughput of about 5000 t/y of a solid recovered fuel obtained from unsorted residual waste, have been quantitatively assessed. Mass and energy balances of the proposed heat gasifier plant for the case study were based on experimental data obtained from a pilot-scale bubbling fluidized bed air gasifier. A mild combustion system has been proposed to burn the syngas and coupled with an Organic Rankine Cycle generator. Economic evaluations have been developed on the basis of the estimation of standard accounting items such as total plant and operating costs as well as revenues from electric energy production and landfill volume savings.

The results indicate that the proposed plant configuration could be sustainable only in presence of an incentive tariff for energy production and only if the plant is integrated in a waste management system, allowing the economic valorization of landfill space saving. The latter appears remarkable since more than 10,000 m^3 can be saved each year after the implementation of the proposed small-scale gasifier.

Acknowledgements

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